Ranger VIII and Gravity Scaling of Lunar Craters

Abstract. *The impact of Ranger VIII gives us the first chance to test the crater-forming process on the moon and to ascertain the existence of gravity scaling.*

Ranger VIII struck the moon in what appears to be a typical mare region. Its mass was 815 pounds, most of it concentrated in a nearly conical body (*1*). Two solar battery wings projected from the base. It was not a typical solid mass such as a meteorite, yet the mass of this object was limited to a volume substantially smaller than the lunar crater it produced. The velocity at impact was 2.653 km/sec (*2*). From these data, the logarithmic kinetic energy at impact was 16.1167 ergs.

In *The Measure of the Moon* (*3*), equations 8-1A, 8-3A, and 8-5A give the relationships between crater diameter and energy applied for three different scaled depths of bursts for craters produced on the earth. In the low-energy range with which we are concerned, the equations are valid for materials like soils rather than solids. The scaled depths of burst are $H/W^{\frac{1}{3}}$ is equal to 0.00, 0.10, and 0.25, where H is the depth of the burst center in feet and W is the weight in pounds of TNT equivalent. The first case is for surface bursts. The second is for a typical meteoritic impact burst as nearly as can be told from study of meteoritic craters (*4*), and the third is for bursts which may be farther below the ground level than is probable for Ranger VIII. If the Ranger VIII impact had been on the earth instead of on the moon, the first and third cases should bracket its crater and the middle one should approximate it.

Similarly, equations 8-2A, 8-4A, and 8-6A will give the relationships between the energy applied and the apparent crater depth. When the Ranger VIII data are substituted into these six equations, $H/W^{\frac{1}{3}}$ is equal to 0.00, 0.10, and 0.25; apparent diameter is 6.64, 7.45, and 8.62 m; and apparent depth is 1.47, 1.85, and 2.16 m.

The Ranger VIII impact point was identified by NASA as a small, intensely white crater, C_1 (Fig. 1). It is in the P-5 Apollo landing site. The larger crater, C_2, was given as a possibility, but C_1 was preferred. The identifications were made by plotting the positions of the central reticle from the six Ranger VIII sets of photographs and finding the most probable valuc for the intersection point of these loci.

The newspaper release by the National Aeronautics and Space Administration on this Ranger VIII crater stated that it was slightly oval, 7 by 9 m, and was 1.75 m deep. My own measurements, which were duplicated by two other people, correspond to a very slightly oval crater with a mean diameter of 7.59 m and a depth of approximately 1.75 m.

Thus the C_1 crater is almost exactly the size it should be if it had been formed in an average soil on the earth by the Ranger VIII impact. However, it was not formed on the earth but was produced on mare material on the moon. We now have to deal with two fundamental unknowns. These are the cohesiveness of the lunar materials and the effect of gravity on the size of the crater produced by a given application of energy.

The Surveyor photographs gave rather convincing evidence that the outer layers of the moon, at least on the maria, are highly fragmented. The way the foot of Surveyor penetrated the moon also suggests a moderate amount of cohesion (*5*) in the outer few centimeters.

The other problem, the effect of gravity on crater dimensions, has not been thoroughly investigated, although its importance has been recognized.

In 1964, Gault and Moore (*6*) wrote that the penetration of missiles producing rather large craters were proportional to the fourth root of the energy, which indicates a fourth-root or gravity scaling. For this type of scaling, the energy spent during crater formation is used primarily to raise large masses of material out of the cavity. Similarly, Chabai (*7*) derived theoretically a fourth-root gravity scaling law. Somewhat later, Moraski *et al.* (*8*) showed that crater dimensions in cohesionless soils varied inversely with the effective force of gravity. Experiments with small explosive squibs were run at 0.17, 0.39, 1.0, and 2.5*g*. Both the experimental and analytical work in their study showed that the shear strength of a cohesionless medium varies directly with gravity.

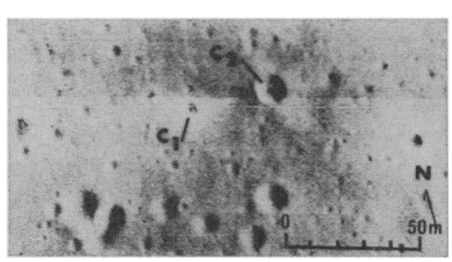

Fig. 1. Craters C_1 and C_2, one of which may have been produced by impact of the Ranger VIII spacecraft. Area shown is in the southwestern part of Mare Tranquillitatis, south-southwest of Sabine EA. From framelets 601 and 602, Lunar Orbiter II frame H-70.

How may these results be reconciled with the observed fact that the C_1 crater is the same size as it would have been if formed in soil on the earth? If the fourth-root scaling were applicable, we would have

$$\frac{r_1}{r_2} = \left(\frac{g_2}{g_1}\right)^{\frac{1}{4}}$$

or

$$\frac{r_1}{r_2} = \frac{1}{1.569}$$

where r_1 is the crater radius on the earth, r_2 is crater radius on the moon, g_2 is the surface gravity on the moon, and g_1 is surface gravity on the earth.

Now, if we choose the theoretical crater diameters as calculated above for the Ranger VIII collision for $H/W^{\frac{1}{3}} = 0.10$ and multiply 7.45 m by 1.569, we should find the Ranger VIII crater to be 11.7 m wide. If $H/W^{\frac{1}{3}} = 0.25$, the crater should be 13.5 m wide. If we accept Moraski's interpretation, the Ranger VIII crater should be 45.2 to 52.3 m wide. The latter case is impossible. The error in measuring the crater diameter does not appear to be larger than about 1 m.

Upon reaching this stage, the identification of the C_1 crater as the correct one was questioned. I plotted the Ranger VIII data and found that all six traces passed close to the C_2 crater and none was near the C_1 crater. The latter is some 30 m to the west. Dr. M. J. Swetnick of the Lunar Orbiter Program furnished the accompanying figure and a transcript of the press briefing. Dr. Gerald Smith of the Jet Propulsion Laboratory had also come to the conclusion that C_2 was the impact crater (*9*).

The work of Gault and his associates has shown that strongly shocked material from under dense media are metamorphosed into a highly reflective substance. This requires a hypervelocity collision (greater than 5 km/sec).

Thus it is not unreasonable to believe that the haloed C_1 crater is a true, recent hypervelocity feature of meteoritic origin, while the larger C_2 crater is the man-made feature produced by the Ranger VIII spacecraft. This conclusion is buttressed by the fact that the larger crater appears to be surrounded by material, some of it rayed, having a lower albedo than that typical of the general region. The anomalous dark material turned up by the impact of the Surveyor I footpads immediately comes to mind. The Ranger VIII impact was not at hypervelocity.

It thus appears highly probable that the C_2 crater is the one produced by Ranger VIII. This crater is 13 m in diameter, in such close agreement with the fourth-root gravity scaling that the latter is probably correct. If fourth-root gravity scaling is correct, it implies that the outer layers of the moon's surface are composed of materials whose cohesiveness is close to that of terrestrial soils, much as Surveyor III has shown them to be. The results of Moraski *et al.* (*8*) would appear not to apply to the Ranger VIII crater.

It should also be pointed out that gravity scaling as here exemplified is effective only when the materials can be put into ballistic trajectories. When compression is the major cratering effect, we are dealing with strength of materials and with mass, which are not functions of gravity. Hence gravity scaling should be a major factor only for those craters formed largely within the outer soil-like layers of the moon. The much larger craters will approach more closely to the size craters the same meteorites would produce on the earth for the same velocity of impact.

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References and Notes

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Distortion of a Splashing Liquid Drop

Abstract. *The low-speed splash of a drop of liquid into a pool can result in a surprisingly complicated flow pattern, apparently not detected by previous experiments or theories. We examined the dynamics of this process by high-speed computer, obtaining a series of configuration plots at various stages of the splash.*

The dynamics of a liquid drop splashing into a pool have been studied experimentally (*1–4*) and by numerical solution of the Navier-Stokes equations (*5*). The experimental results have been obtained principally by high-speed photography. They show especially well the behavior of the free surface through the following sequence of events: (i) A crater is formed and fluid

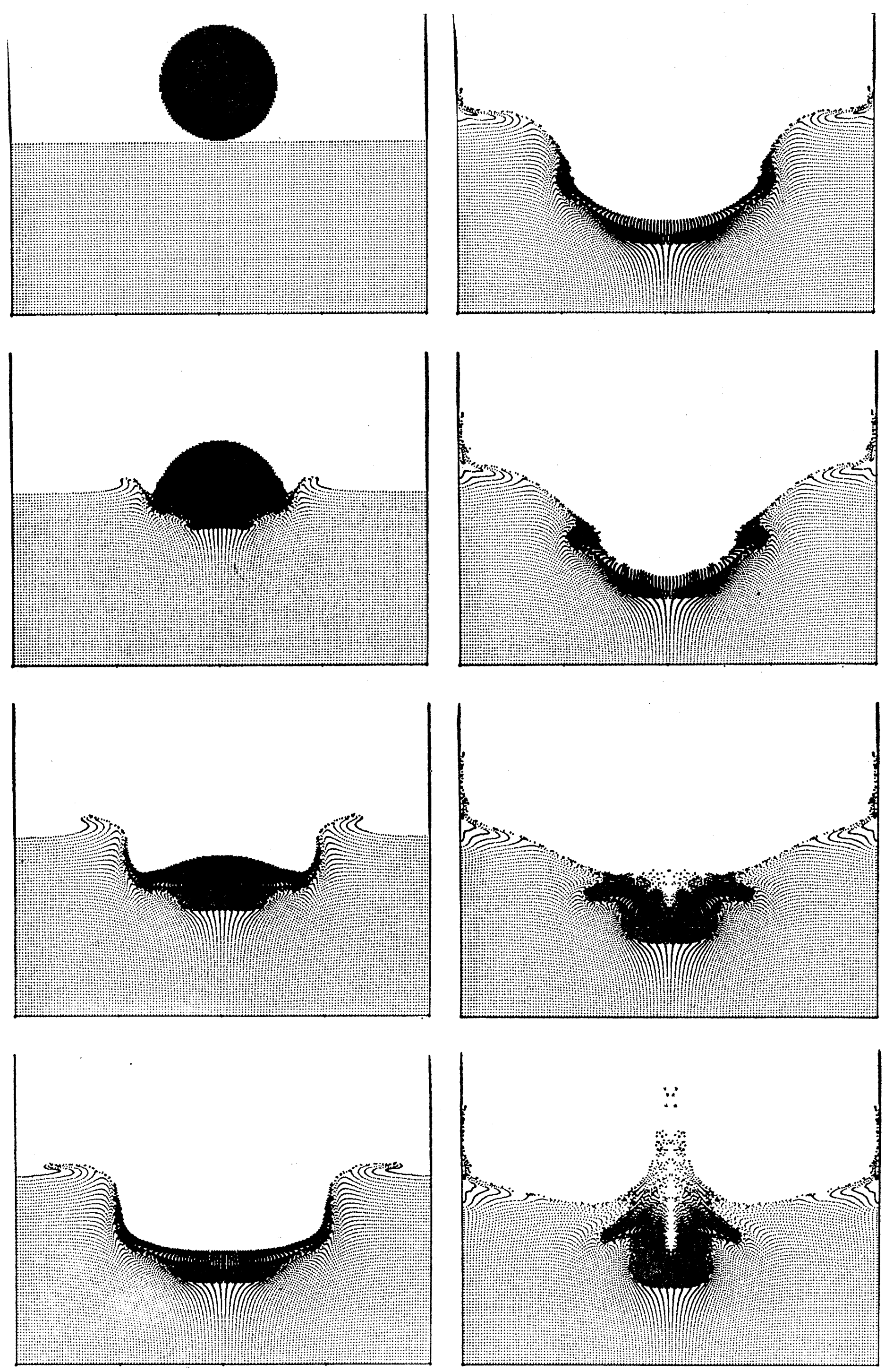

Fig. 1. Cross section of splashing drop with $u_0 = 2.0$. Frames (read left, down; right, down) are at $t = 0, 5, 10, 15, 20, 25, 30,$ and 35.